Mechanical Regulation of Burn Wound Scarring through Compression Garment Therapy

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Background

Pressure garments have been utilized for over 50 years to aid in wound healing following full thickness burn injuries. These pressure garments are believed to constrict the flow of blood, nutrients, and oxygen to the wound, limiting collagen synthesis to prevent scar tissue formation and enhance skin pliability[1]. Yet, though this therapy has been around for half a century, there has not been thorough research to understand the biomechanical and biochemical impacts that the therapy has on the wound healing/scarring process. With enhanced understanding of the operating mechanisms, the therapy could be greatly improved in terms of effectiveness and comfort for the patient. For example, current clinical use requires a patient to wear the garment 23 of 24 hours a day for up to 2 years. Compliance rates, with young children specifically, are estimated to be as low as 40%. Thus understanding the daily duration of efficacy and optimal applied pressure may reduce wear times and in turn increase compliance. The purpose of this study was to quantify pressure generated by compression garments on the underlying skin as a function of duration of wear, to assess the anisotropic properties of different garment fabrics, to test both the material and chemical properties of each of the fabrics used in the manufacture of the garment, and to study the effects of laundering the garments[2].

Degrees of Burn Severity

There are varying degrees of severity with burn wounds. First degree burns penetrate only through the epidermis, the outer layer of skin. Second degree burns go beyond the epidermis into the underlying dermis layer of skin. Third degree burns, also known as full thickness burns, reach down to the subcutaneous fat layer. Forth degree burns go beyond the fat layer into muscle and/or bone. For the purpose of this study, only full thickness burn wounds will be considered[3].

Hypertrophic Scarring

If a person experiences a full thickness burn wound, they will first undergo an immediate, acute immune response from the body. Neutrophils and monocytes will migrate to the site of the wound to clean out the dead cells and destroy any infectious agents that may have invaded through the open wound. After that process is completed, nearby fibroblast cells will start over-producing collagen and depositing it where the healthy tissue used to be. This collagen remodels into scar tissue over the course of several years and the result is what is known as hypertrophic scarring[4]. Hypertrophic scars are raised above the skin, contract the surrounding skin during formation, typically have less pigmentation (coloring of the skin), and have a different composition than healthy skin. These scars are mainly composed of collagen I fibers aligned in fairly organized bundles. This is starkly different from the normal extracellular matrix in skin tissue composed of layered collagen III and collagen I fibers that overlap in differing angles to provide a lattice-like pattern. Hypertrophic scars, especially when they are located near a joint, make movement painful and difficult. They can limit a person's range of motion and provide lifelong complications[5].

Compression Garment Therapy

Compression garment therapy varies depending on which clinic is administering it. Custom garments made from an elasticized fabric need to be constructed to provide a specific range of pressures across the affected burn area. The therapy relies on the compression provided by this custom design, so tailoring the garments to the individual is very important. There are several problems that arise from the current protocol for treatment. First, the social stigma that patients experience, especially young patients, from wearing the garments in public is debilitating and embarrassing. Since each garment is custom-made and must be replaced, the high cost of fabricating each garment is problematic for many patients. In high temperatures, the garment can trap in moisture and become very uncomfortable. During everyday use, the garment can cause blistering of the skin. Finally, in younger children especially, the pressures provided by the garment can cause abnormal bone growth and lead to further complications. By studying the structural properties of the garment and biomechanics of the skin during compression garment therapy, a more effective garment can be developed to reduce the total wear time required for successful treatment[6,7].

Materials and Methods

Fabric Material

The garments can be composed of nearly any type of elasticized fabric, but for the scope of this study only two of the most frequently used fabrics were tested: moleskin and powernet. Moleskin is commonly used to prevent the aggravation of blisters on the heels of feet. It is composed of high viscosity polyamide nylon 6. Powernet is a composite of nylon and spandex with a ratio of 9:1 respectively. Powernet is often used in lingerie and has a meshed texture that is not as comfortable to feel as the silky texture of the moleskin. Laundering of the garments was done in a washing machine set to cold using Tide laundry detergent. Strips used during the energy dissipation testing were cut at three different orientations of 0°, 45°, and 90° with respect to the edge where the fabric was cut from the spool. The strips were 1 cm by 7 cm in dimension.

Torsional Ballistometer

A torsional ballistometer is composed of a 25cm probe and a data acquisition unit. It is a non-destructive biomechanical assessment device to gauge the elasticity of skin tissue. The probe contains a small stylus arm suspended at equilibrium in a wire coil. A solenoid activates to propel the stylus upward and away from the surface of the skin. It then oscillates around the balance point until equilibrium is once again reached, striking the surface of the skin each time. An optical sensor within the probe monitors the arm position. The data is affected by the mechanical properties of the skin and the impact energy, which is preset by the user so that the stylus delivers a constant kinetic energy and can be used at any orientation since it is independent of gravity. An exponential curve fit to the peaks of the data contains an alpha value that represents the rate of energy damping. Large alpha values indicate high-energy absorption signifying a more in-elastic material[8].

Fourier Transform Infrared Spectroscopy (FTIR) with Attenuated Total Reflection

Fourier Transform Infrared Spectroscopy is a method for determining the chemical composition of a material. An infrared light beam is passed through a sample. Molecular bonds selectively absorb certain wavelengths causing a change in dipole moment. The machine then analyzes the unabsorbed light to determine how much was absorbed by the bonds in the material. The data output is the intensity of each wavelength of light. The device is able to detect a broad range of wavelengths to give a relatively complete readout of the material composition, giving this technique an advantage over more traditional dispersive spectroscopy. Attenuated Total Reflection is added in conjunction with FTIR to make examination of each sample consistent with every other examination to eliminate some confounding variables that can occur between testing.

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy produces images by focusing a beam of electrons onto the surface of a prepared sample that has been coated with a conductive material, typically gold. The primary electrons from the beam interact with the gold on the surface of the material and cause it to release secondary electrons. The secondary electrons are collected on a scatter plate and used to construct the image of that section. Scanning the beam over the entire surface of the sample creates the full image. The resolution of SEM is around 10 nm, giving it a significant advantage over light microscopy. The fabric samples were sectioned, mounted, coated in a thin layer of gold, and imaged at 36x magnification.

Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy is used to image a specimen by passing a beam of electrons through it. Only a thin sample is typically used since the electrons must pass through the entire material. Electrons interact with the internal atoms of the specimen and produce a two dimensional image of an internal layer of the sample. The resolution of TEM is around 0.2 nm, giving it a significant advantage in resolution over light microscopy and even an advantage over SEM. Skin samples were sectioned and sampled to look at the collagen fibril structure of the tissue.

Fabric Fatigue Testing

A human-shaped torso made of a polyurethane compound molded over urethane foam was used to test the compression of the garment over time in a static environment. The exterior of the dummy has the feel and resiliency of human flesh. Pressure gauges were placed at 5 key anatomical locations that had a high radius of curvature to monitor the compression. Custom vests were constructed out of each fabric and placed on the dummy for 23 hours. Figure 1 shows the dummy with the gauge locations identified, as well as the dummy wearing each vest.

Figure 1: Test dummy for testing garment compression over time

Results

Preliminary *in vivo* Study

A preliminary study was conducted on Red Duroc pigs to assess the efficacy of compression garment therapy. Each pig was administered eight 1in^2, full thickness burn wounds on their back using a custom soldering apparatus. A graphic of the burn pattern can be seen in Figure 2.

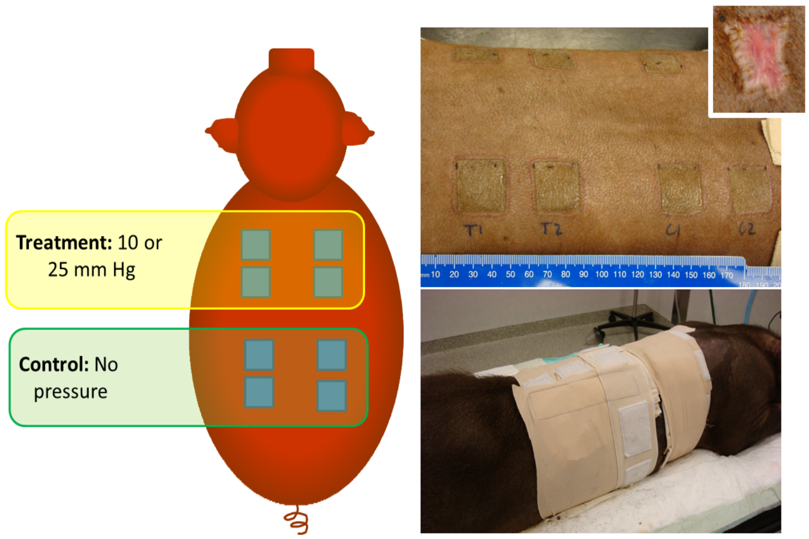

Figure 2: *Left:* Diagram of the burn locations on the back of the pig.
Right: A pig wearing the garment

Half of the wounds were treated with compression garment therapy starting at 28 days post-burn. The garments were custom made using the moleskin fabric. At 72 days the pigs were euthanized and biopsies were taken to be tested for strength. Throughout the 72 day period the pigs had their garments changed and their wounds analyzed for contraction. Wound contraction was determined based on the visible area of the wound. The data is shown in Figure 3. From the data, the wounds had no significant differences in contraction until after 56 days. By the end of the study, the control burn wounds had contracted roughly 20% more than the treated wounds.

More contraction should result in a stiffer scar tissue, but this needed to be verified. A non-destructive technique using a torsional ballistometer was used on the skin of the control and treated burn wounds at the conclusion of the study to assess elasticity. Results can be seen in Figure 4. The 'burn' data was from the untreated wounds and absorbed more of the kinetic energy from the probe with each strike from the stylus arm, indicating that it is a more in-elastic material. The 'burn + compression' was from the treated wounds and closely follows the absorption rate of normal pig skin. This indicates that the treated scar tissue is similar in elasticity to normal pig skin, which is desirable to increase the compliance of the tissue and increase the patient's mobility.

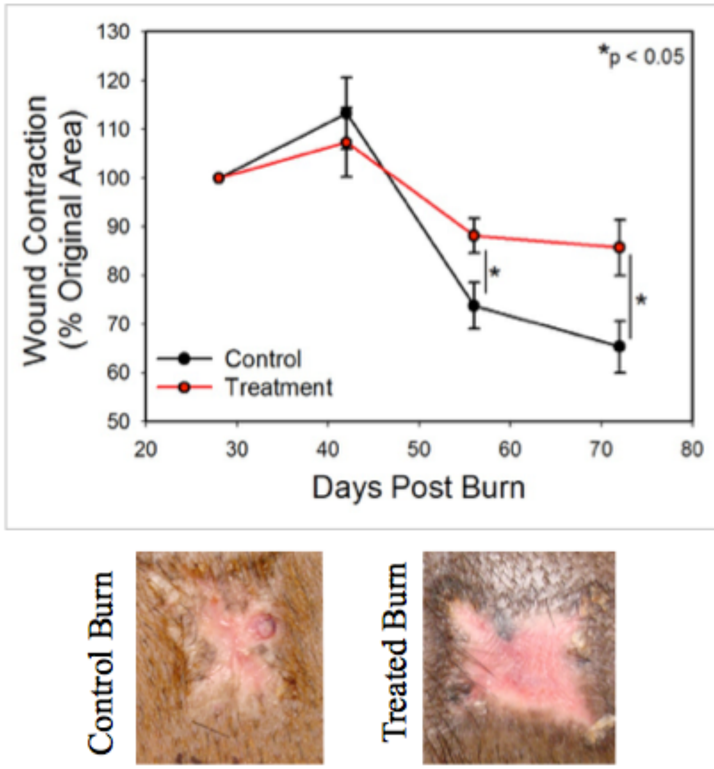

Figure 3: *Top:* Wound contraction results. *Bottom:* Sample wound images

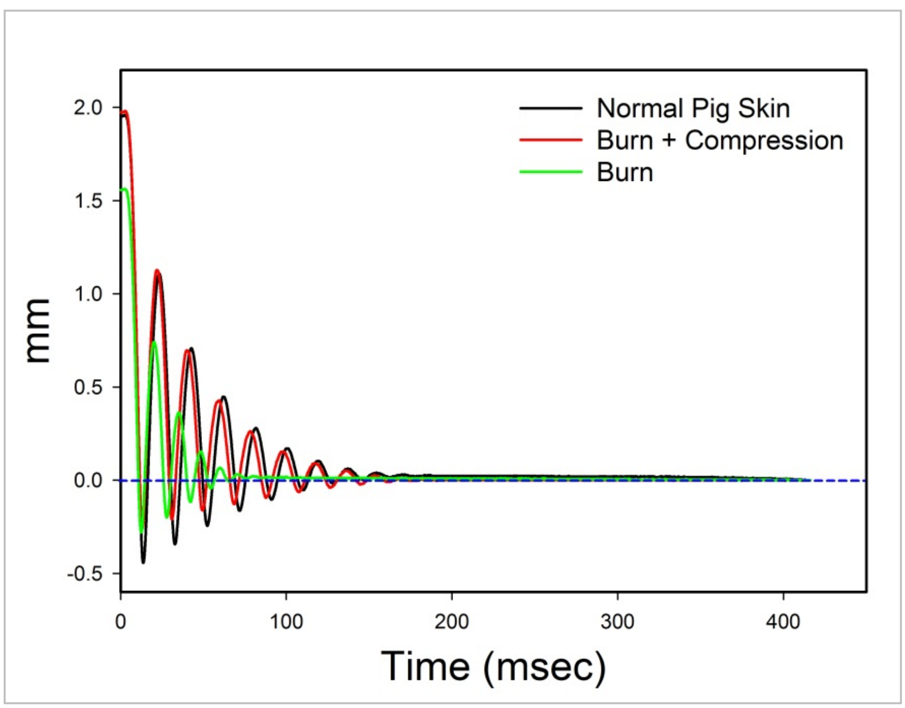

Figure 4: Non-destructive biomechanical assessment using a torsional ballistometer

The biopsies taken when the pigs were euthanized were put into a tensile tester and pulled at a constant strain to record the stress exerted through the tissue. The maximum stress recorded was used to indicate the ultimate tensile strength of the tissues. Ultimate tensile strength data is shown in Figure 5.

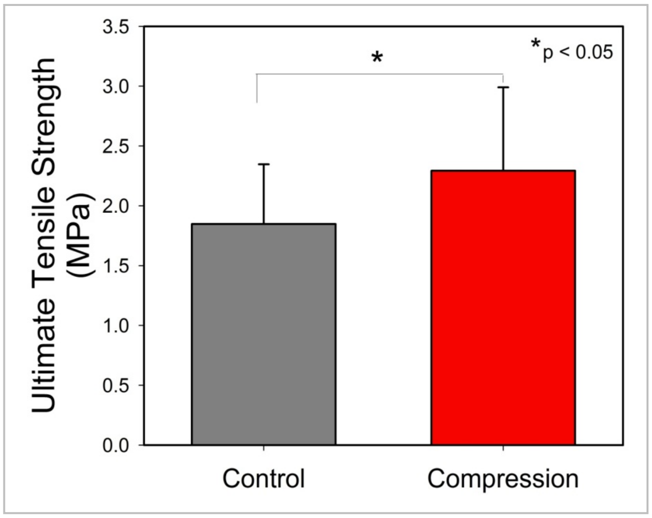

Figure 5: Ultimate tensile strength of the control group and treated group of wounds

The treated wounds showed significantly higher strength than the control group. This could be at least in part due to the differences in collagen organization and shape between the two groups. Figure 6 shows a TEM cross-section of the collagen fibrils in each type of scar tissue. The gray circles are sections of each fiber. The treated group had smaller diameter fibrils on average and more consistent shape than the control burn wounds. This increase in the number of collagen fibrils per volume of tissue, along with the consistent shape, could be the cause of the increased strength of the treated tissue compared to the control tissue.

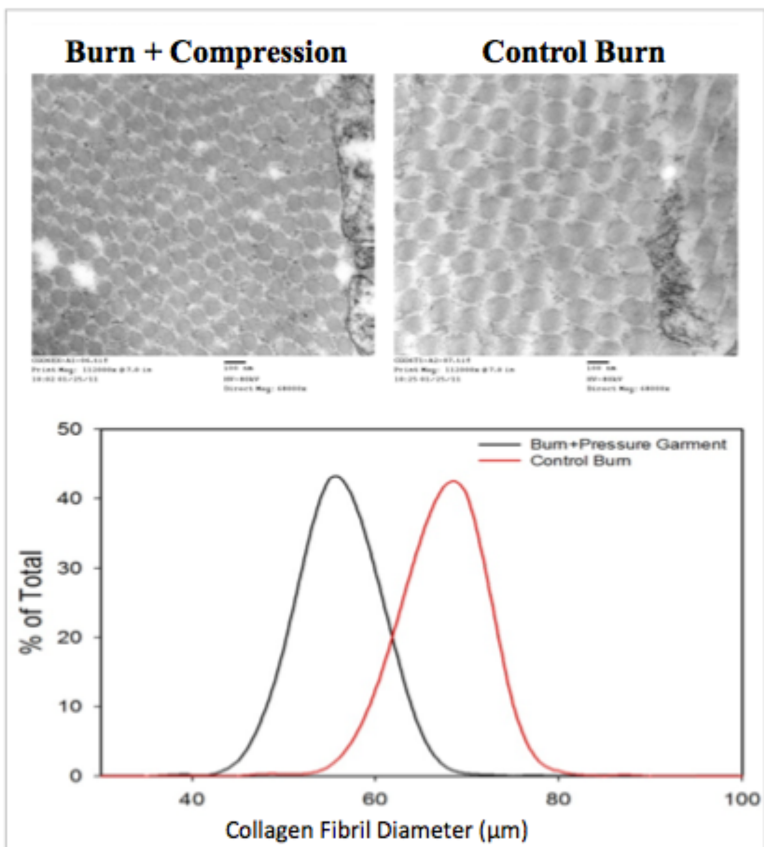

Figure 6: TEM collagen fibril cross-section

Energy Dissipation

Having shown some efficacy of the therapy, focus moved on to the properties of the garment fabrics themselves. Both fabrics were tested at three different orientations to test for anisotropic differences in the energy dissipation of the fabric through cyclic fatiguing. Small strips were cut from both fabrics at 0°, 45°, and 90° with respect to the edge where the fabric was cut from the spool. A diagram of these orientations can be seen in Figure 7.

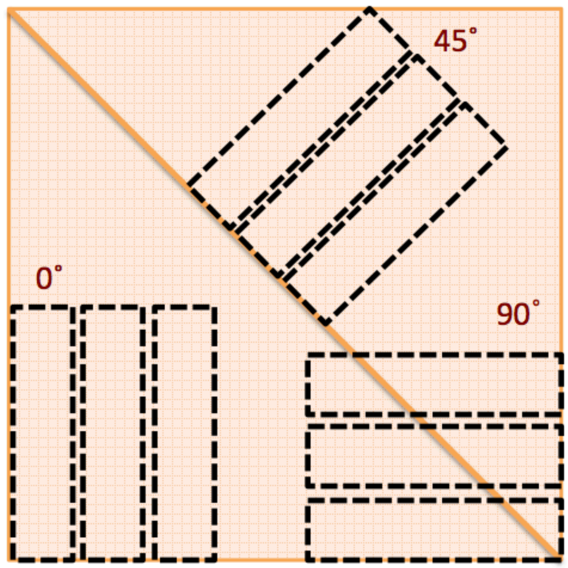

Figure 7: Diagram showing the different orientations of cut fabric

These strips were strained to 5mm repeatedly while the load was measured in a tensile tester. The resulting data is known as a hysteresis curve, a sample of this can be seen in Figure 8.

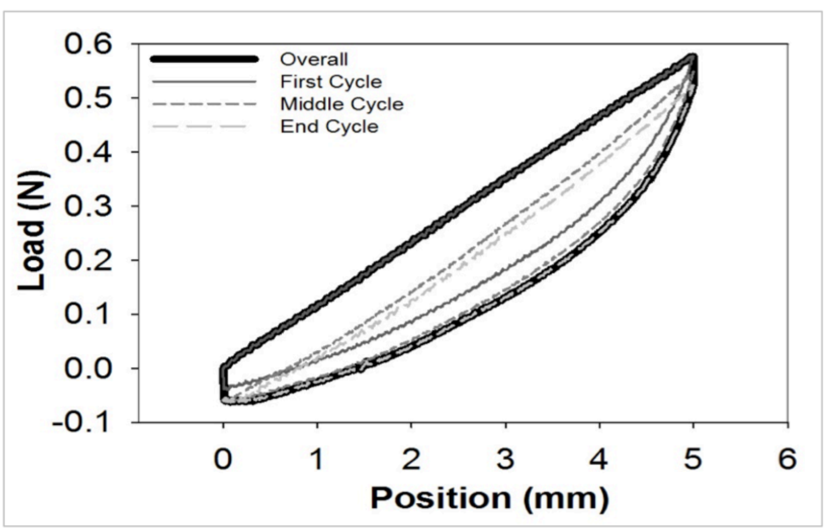

Figure 8: Sample hysteresis curve

The energy dissipation of the fabric is calculated based on the difference in area of the hysteresis curves of each successive cycle. The data was compiled and can be seen in Figure 9.

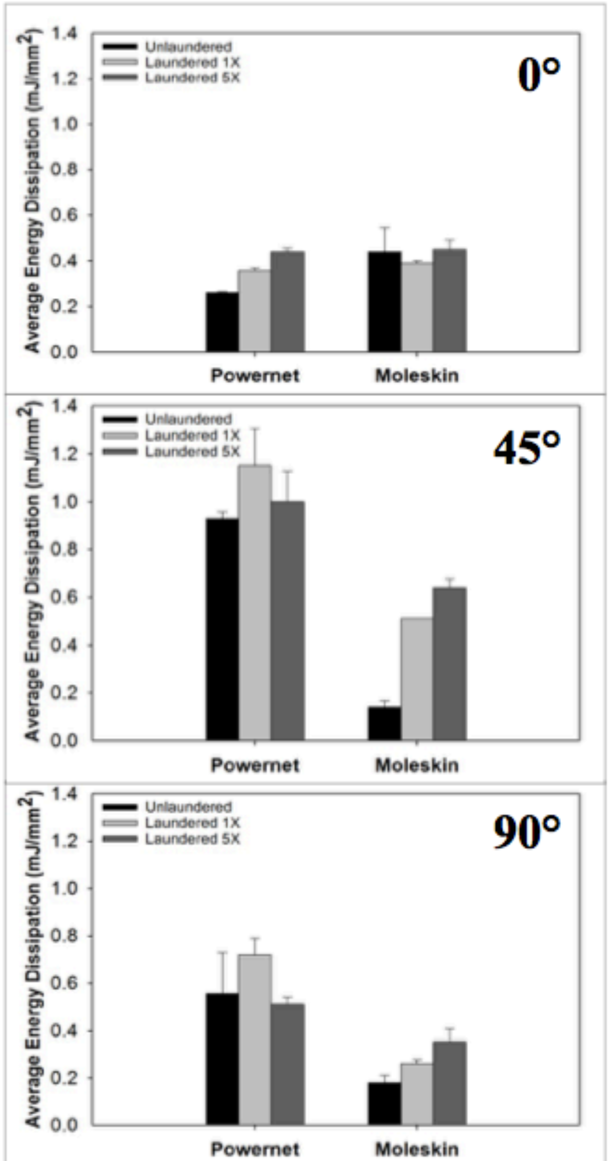

Figure 9: Energy dissipation of each garment at each orientation

The greater the energy dissipation, the less effective the fabric will be in maintaining a constant pressure over the skin during wear. Thus, the most effective orientation will be the one with the least amount of energy dissipation across each amount of laundering (unlaundered, laundered one time, and laundered five times). For the powernet fabric, the 0° orientation lost the least amount of energy and would be the most effective orientation. For the moleskin, the 90° orientation lost the least amount of energy and would be the most effective orientation.

Pressure Over Time

Next, vests constructed of each type of fabric were placed on the test dummy and measured for their applied compression over a 23-hour period. The results can be seen in Figure 10.

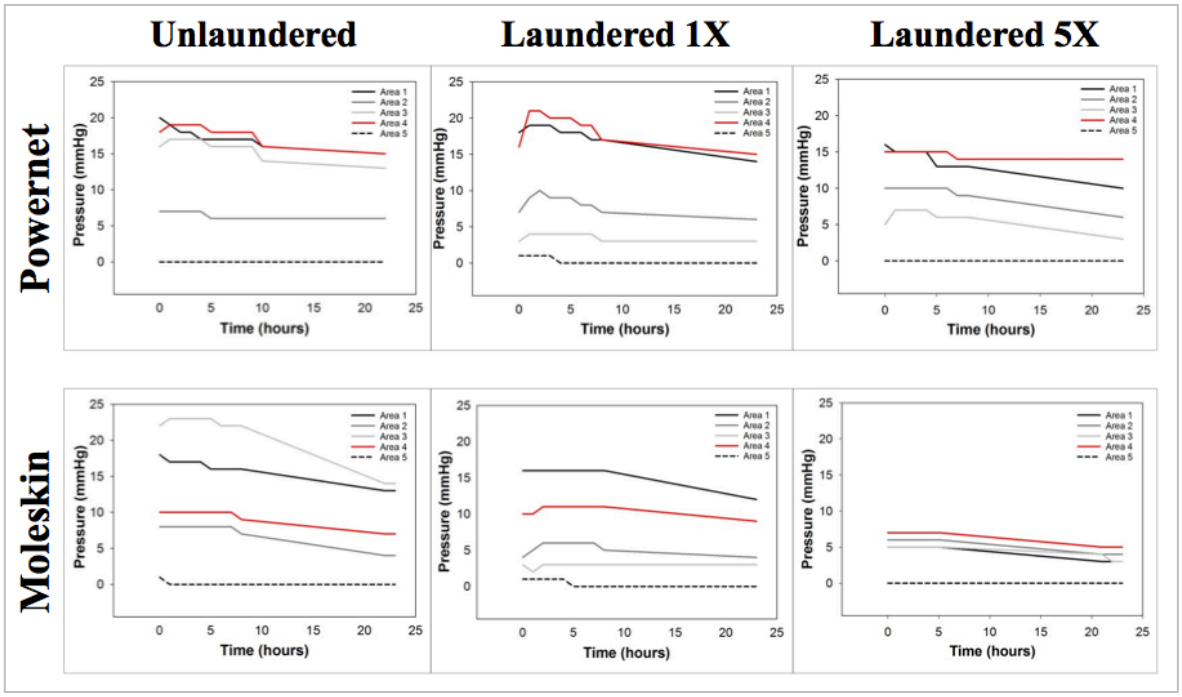

Figure 10: Pressure testing over time at 5 key, anatomical locations

The first thing to note here is that for all of the tests the pressure dropped over the 23-hour period, sometimes by as much as 10 mmHg. The current target range of pressure for compression garment therapy is 15-20 mmHg. Some of the pressure gauge locations, especially gauge #5, do not experience nearly as much pressure as the other locations. This highlights one of the difficulties with compression garment therapy, as it is very difficult to account for the irregular curvature of the human body to apply consistent pressure. Looking at the affects of laundering, the more laundering the garment undergoes, the less affective it is at maintaining constant pressure over time. This is especially true with the moleskin fabric, which should diminished performance after only one laundering, and significantly diminished performance after five launderings. The powernet fabric holds up much better to laundering.

Surface Imaging

To better understand how laundering the garments affects their ability to hold pressure, the fabrics were imaged using SEM at different launder cycles. These images can be seen in Figure 11. The imaging showed no apparent change in the physical geometry of the fabrics beyond random variation between locations on the garment.

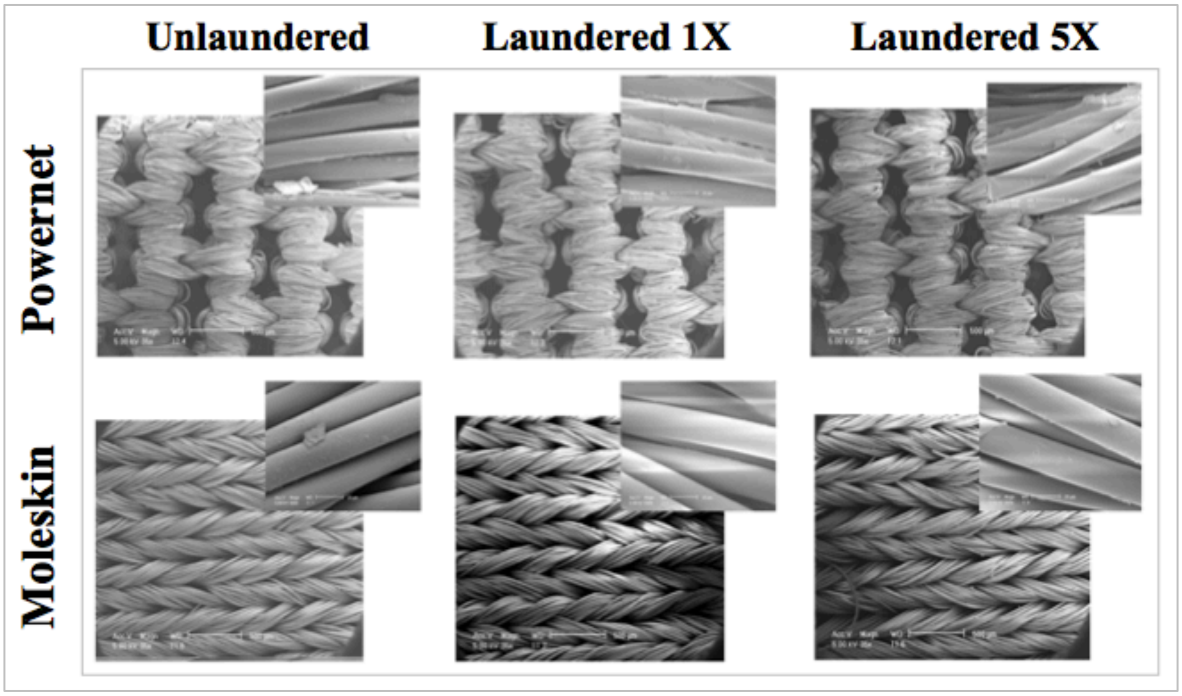

Figure 11: SEM images of the surface geometry of both fabrics at different launder cycles

Chemical Composition

Since the surface imaging gave little indication as to how laundering affects the garment fabrics, FTIR was used to exam how the chemical composition changes with laundering. FTIR results for the moleskin fabric and the powernet fabric are shown in Figure 12 and Figure 13 respectively. In the moleskin graph, the important wavelengths are 1635 cm^{-1} (amide I bonds) and 1543 cm^{-1} (amide II bonds) being that moleskin is a polyamide material. After successive launder cycles, the amount of amide I & II bonds decreases, but not a significant amount. This could be due to degradation of the bonds as a result of interacting with the detergent.

Looking at the powernet results, however, suggests a different story. After one laundering, the amount of spandex bonds is about the same as before the fabric was laundered, but the amount of amide bonds has decreased. After five launderings, this has flip-flopped where now there is a larger amount of amide bonds and a decreased number of spandex bonds. There could be several reasons for these results. The fabric could just be heterogeneous so measuring different locations yields different results. Another possibility is that there could be interference with the readings due to residue left behind by the detergent. Finally, there could still be a degradation affect where there are bonds being broken by the interaction with the detergent, but this could expose different layers of the material exposing a different ratio of bonds. It is difficult to tell from these data alone which explanation is accurate or if it is due to a different cause. Further testing needs to be done to confirm one explanation or another.

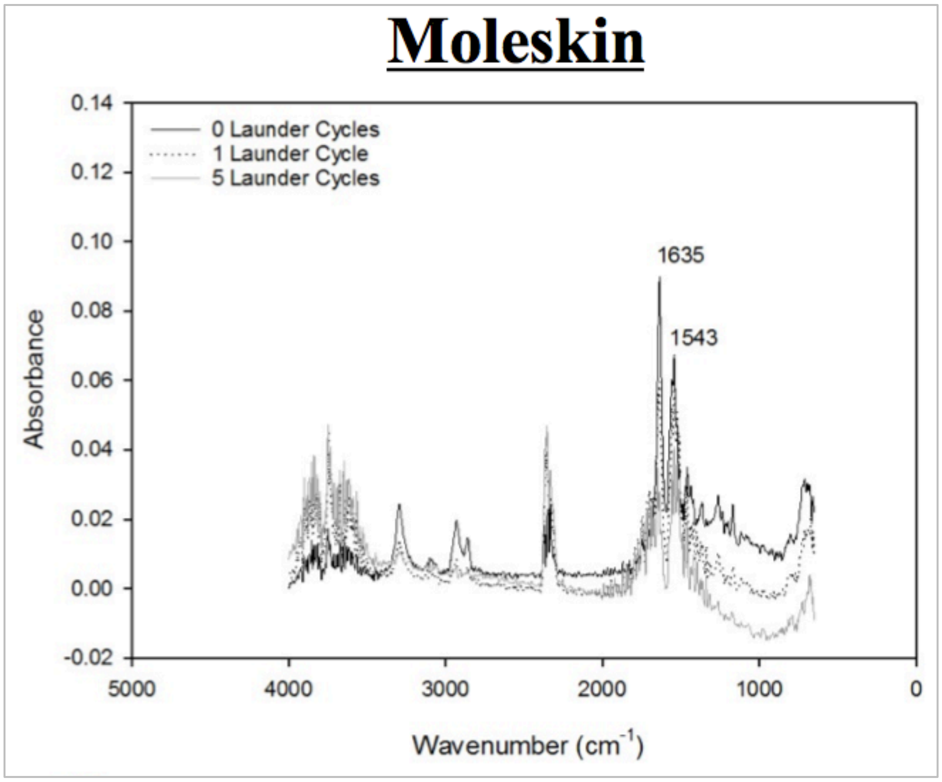

Figure 12: FTIR chemical composition of moleskin fabric over launder cycles

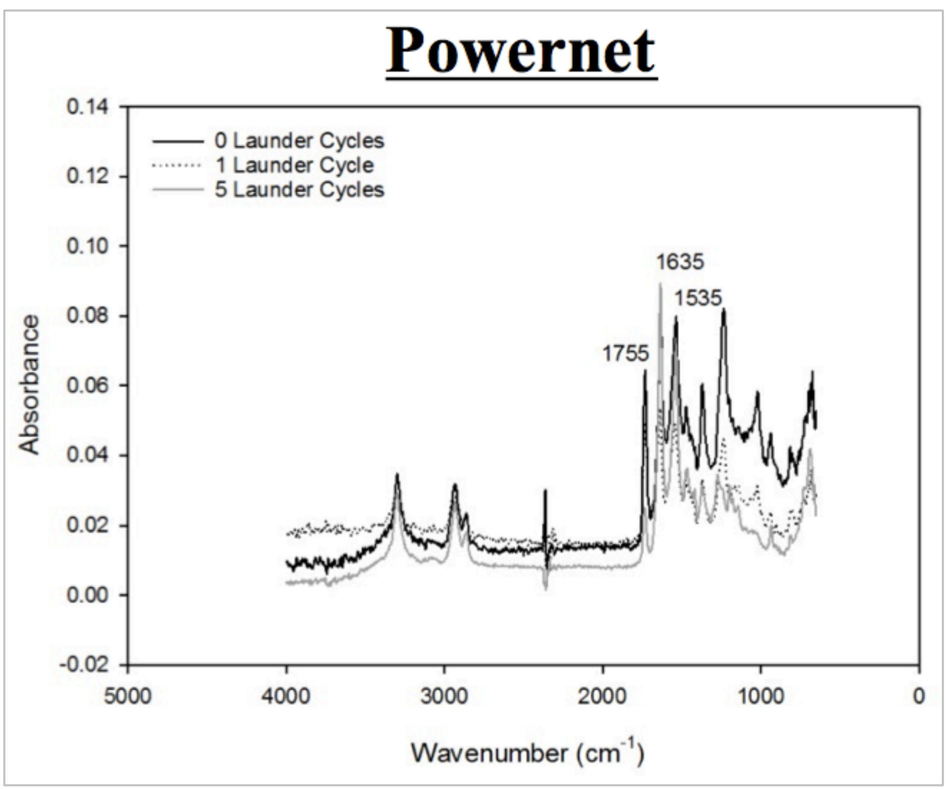

Figure 13: FTIR chemical composition of powernet fabric over launder cycles

Conclusions

Based on the energy dissipation testing, powernet fabric operates most effectively when stressed along the 0° orientation, while moleskin operates most effectively when stressed along the 90° orientation. Powernet holds constant pressure more effectively than moleskin when on the dummy making it a more suitable material for garment use. Even when using powernet, however, there is loss of pressure over a 23-hour period of time. Due to the complex surface geometry of the human body, the current compression garments have difficulty administering equal pressure to the entire torso. Laundering garments up to five times caused no significant exterior structural alterations to either fabric. In the powernet fabric, laundering caused a shift in the levels of amide I&II compared to spandex exposing mainly spandex after one laundering and mainly nylon after five launderings. This suggests that there is either some effect of laundering on the bonds in the fabrics, or the testing procedure was flawed.

Going forward with other *in vivo* studies of compression garment therapy on Red Duroc pigs, powernet fabric oriented at 0° is being used to construct the garments. Many studies are ongoing including one that is testing whether earlier intervention can improve the therapy. The therapy is being administered at 7 weeks and 35 weeks to see how earlier and later intervention affect the scar development process. Compression garment therapy is also being paired with autograft meshing and laser perfusion to further aid in the healing process. All studies are being conducted in order to better understand the process of compression garment therapy to develop more effective garments and protocols to reduce the total wear time of the patient.

Acknowledgments

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